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Optimal shape design of multi-element trawl-doors using local surrogate models

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ABSTRACT

Trawl-doors have a large influence on the fuel consumption of fishing vessels. Design and optimization of trawl-doors using computational models are a key factor in minimizing the fuel consumption. This paper presents an optimization algorithm for the shape design of trawl-door shapes using computational fluid dynamic (CFD) models. Accurate CFD models are computationally expensive. Therefore, the direct use of traditional optimization algorithms, which often require a large number of evaluations, may be prohibitive. The proposed approach is iterative and uses low-order local response surface approximation models of the expensive CFD model, constructed in each iteration, to reduce the number of evaluations. The algorithm is applied to the design of a multi-element trawl-doors, involving up to four design variables controlling the angle of attack and the slat and flap position and orientation. The results show that a satisfactory design can be obtained at the cost of a few iterations of the algorithm.

1. Introduction

Trawling gear is a major contributor to the fuel expenditure of many fishing vessels. As most of the fuel is spent during trawling (often over 60%), there is a great incentive to reduce the drag of the fishing gear. The main parts of a fishing gear assembly are the net, a pair of trawl-doors, and a cable extending from the trawl-doors to the boat and the net (see Fig. 1(a)). The role of the trawl-doors is to keep the net open during the trawling operation. Typically, their span is 6–8 m and chord 2–3 m, while the cables are a few hundred meters long and the net tens of meters. Fig. 1(b) shows a typical trawl-door. Although the trawl-doors are small compared to the other fishing gear components, they may be responsible for roughly 10-30% of the total drag of the entire assembly [1]. During trawling, the drag of the fishing gear is much greater than the drag of the ship. Therefore, significant fuel consumption savings may be possible by careful design and optimization of trawl-doors.

Trawl-doors function much like aircraft wings, i.e., they maintain certain lift for a given operating condition. Most trawl-doors developed in the past are fundamentally the same and only minor design changes have been observed. The reason is that their designs are based on time-consuming and expensive physical experiments in tow- or flume tanks. Although computational fluid dynamics (CFD) is widely used for the design of a variety of vehicles and engineering devices, such as aircraft, ships, and cars, very few CFD-based studies are reported for trawl-doors in the literature [2].

Aerodynamic (or hydrodynamic) shape optimization (ASO) involves the search for the best design (or adjustment of an existing one) of an aerodynamic (or hydrodynamic) surface. In practise, this is realized by coupling computational simulation models with optimization algorithms to find the design which improves a measure of merit subject to constraints.

Hicks et al. [3] are generally credited for the first practical application of ASO where they used a conjugate-gradient method to design two-dimensional airfoil shapes in transonic flow. Nowadays, ASO is routinely used to design aerodynamic systems, see for example [4–9]. Gradient-based methods are considered the state-of-the-art in ASO and are the most widely used approaches (cf., [3–5]). These methods can very efficient for a small design space, i.e., when the number of design variables are less than 3. For larger design spaces, adjoint sensitivity is necessary [4]. Still the cost can be prohibitive because gradient-based methods require a large number of model evaluations and each flow analysis can be computationally expensive (on the order of 24 h for a three-dimensional wing shape on a massively parallel system). Other types of algorithms used for ASO are, for example, derivative-free methods [6,10], and one-shot methods [11,12]. However, these methods are typically not as efficient as the gradient-based ones.

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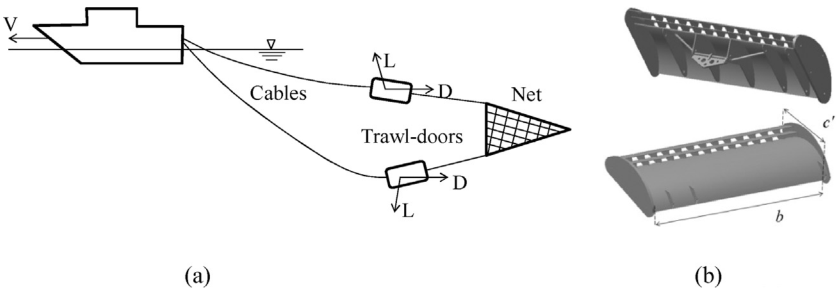

Fig. 1. Schematic of a fishing vessel with trawling gear illustrating (a) the main parts of the fishing gear (not drawn to scale), and (b) a typical trawl-door with two slats.

Surrogate-based methods [13,14] replace an expensive model by a cheap surrogate with the main objective to accelerate the optimization process by using fewer evaluations. Typically, the function-approximation surrogate models are used, i.e., constructed by using design of experiments and data fitting [13–16]. Function-approximation models are versatile, however, they normally require substantial amount of data samples to ensure good accuracy. Typically, these methods consider the entire design space when constructing the surrogate model. Examples of SBO with various function-approximation models can be found in [17–19].

Recently, we introduced a surrogate-based design optimization approach for trawl-doors using two-dimensional CFD models [20,21]. The approach can be categorized as being a variable-fidelity optimization method since it uses a corrected low-fidelity model to speed up the design process. In particular, the method utilizes space mapping [22] and a low-fidelity CFD model to construct a fast and reliable surrogate of a computationally heavy high-fidelity CFD model. Satisfactory designs can be achieved with the approach at low computational cost. However, the approach can be sensitive to numerical noise associated with the low-fidelity CFD model (the numerical noise levels are typically low in the high-fidelity models). Significant numerical noise present in the computational model may impact the optimization process since (1) the design space will be multi-modal, and (2) the low-fidelity model will not follow the overall trend of the high-fidelity model. In both these situations, the optimized design may be different than the one obtained by optimizing the high-fidelity model directly.

This paper presents a new approach to the CFD-based design optimization of trawl-door shapes. The proposed methodology is based on work in the area of microwave antenna design [23] and exploits an iterative scheme with local response surface approximation (RSA) models of the expensive CFD trawl-door model constructed in each iteration. The RSA models are constructed using CFD data sparsely sampled in the vicinity of the current design, and a low-order polynomial approximation (to reduce the influence of the CFD model numerical noise on the optimization, as well as minimizing the number of required data samples). The size of the vicinity (i.e., the RSA model domain) is automatically adjusted in each iteration based on the performance of the model, more specifically, on the quality of the prediction given by the model as compared to the actual changes of the trawl-door performance metrics verified by the CFD simulation. The adjustment scheme is governed by a conventional trust region framework [24]. We demonstrate our approach with examples involving the design of multi-element trawl-door shapes using a high-fidelity two-dimensional CFD model.

2. Problem formulation

The design goal is to optimize the shape and configuration of trawl-doors. The design of other components of the trawling gear are not considered here. We setup the trawl-door using airfoil profiles as proposed in our earlier work [20,21]. However, previous work only considered single-element configurations. Now we consider multi-element configurations as shown in Fig. 2 which has a leading-edge slat and a trailing-edge flap.

The objective function is to minimize the drag of the trawl-door for a given lift to ensure sufficient opening of the net. In particular, the optimization problem is formulated as

$$\min C_{\mathrm{d}} \tag{1}$$

subject to

$$C_{\mathrm{l}} \geq C_{\mathrm{l}}^{*} \tag{2}$$

where C_{d} the drag coefficient (a nondimensional form of the trawl-door drag), C_{l} is the lift coefficient, and $C_{\mathrm{l}}{}^{*}$ is minimum allowable lift coefficient.

The position and inclination of the elements are the design parameters. The design variable vector can be written as

$$x = [x_{\mathrm{s}}/c\, y_{\mathrm{s}}/c\, \theta\, x_{\mathrm{f}}/c\, y_{\mathrm{f}}/c\, \delta_{\mathrm{f}}]^{\mathrm{T}} \tag{3}$$

where x_{s}/c is the slat leading-edge position on the x-axis, y_{s}/c is the slat leading-edge position on the y-axis, θ is the slat inclination relative to the x-axis, x_{f}/c is the flap leading-edge position on the x-axis, y_{f}/c is the flap leading-edge position on the y-axis, δ_{f} is the flap inclination relative to the x-axis, and c is the length of the main element ($c = 1$ in this study). Upper and lower bounds are prescribed on the design variables.

The size and shape of the elements is fixed. The operating condition (the speed V_{∞} and the angle of attack α) is also fixed during the optimization.

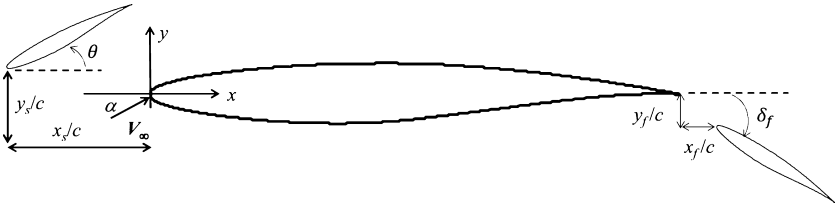

Fig. 2. A section cut of a trawl-door with airfoil shaped elements, including a leading-edge slat and a trailing-edge flap.